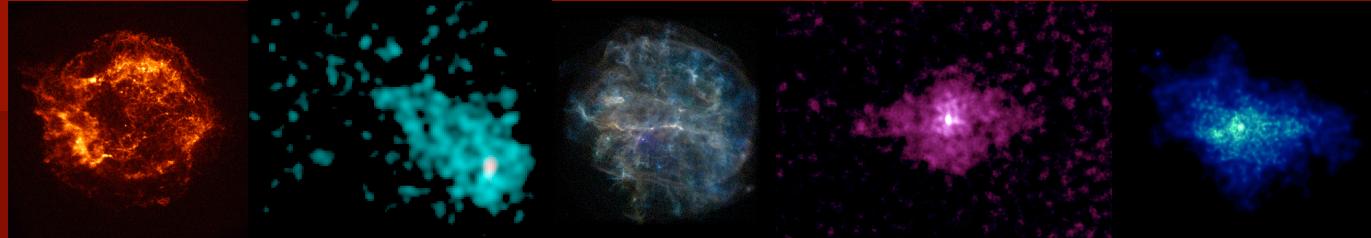


# Spatial/Spectral Studies of Supernova Remnants with *Chandra* and *XMM-Newton*

John P. Hughes

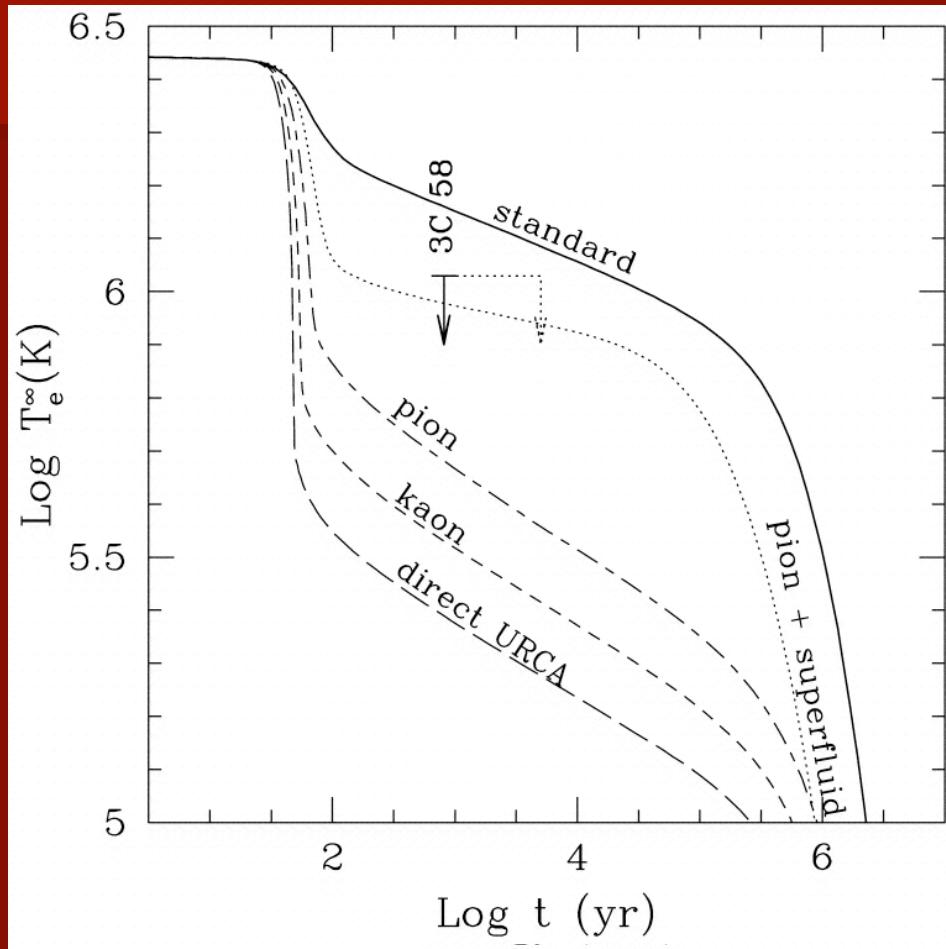
*Rutgers University*

# New Pulsars and CCOs



Cas A	CXOU J232327.9+584842	CCO
PKS 1209-51/52	1E 1207.4-5209	424 ms (X-ray)
G106.3+2.7	PSR J2229+6114	51.6 ms (radio)
IC 443	CXOU J061705.3+222127	CCO
G292.0+1.8	PSR J1124-5916	135 ms (radio)
RX J0852.0- <sub>4622</sub> 3C 58	CXOU J085201.4-461753	CCO
G54.1+0.3	PSR J0205+6449	65.7 ms (X-ray)
	PSR J1930+1852	136 ms (radio)

# 3C 58 and NS Cooling



- ▼ Crab-like remnant
- ▼ Associated with SN 1181
- ▼ 65.68 ms PSR (Murray et al. 2002)
- ▼ Distance 3.2 kpc
- ▼ Spectrum of central source (Slane et al. 2002)
  - Power law:  $\Gamma = 1.7$
  - $T_{BB} < 1.08 \times 10^6$  K for 12 km radius neutron star
- ▼ Below “standard” NS cooling curve

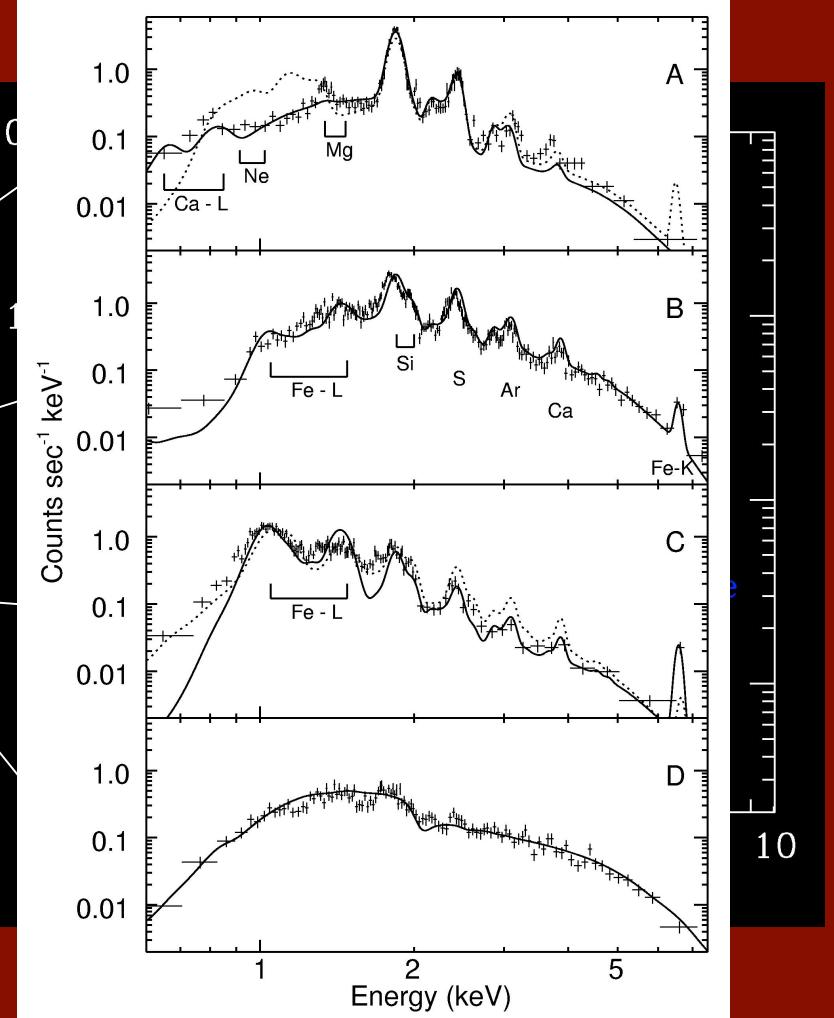
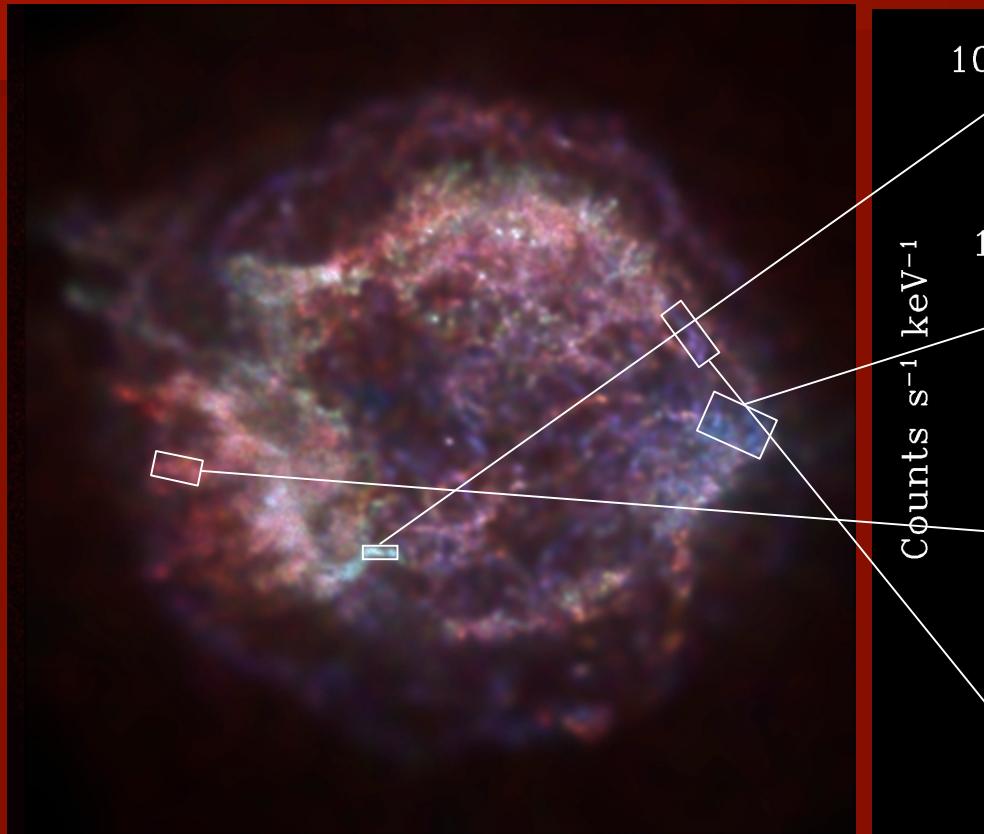
# Nucleosynthesis in CC SNe

- ▼ Hydrostatic nucleosynthesis
  - During hydrostatic evolution of star
  - Builds up shells rich in H, He, C, O, and Si
  - Amount of C, O, Ne, Mg ejected varies strongly with progenitor mass
- ▼ Explosive nucleosynthesis
  - Some mechanism drives a shock wave with  $10^{51}+$  erg through the Fe-core
  - Burning front T's of  $\sim 10^9$  K cause explosive O- and Si-burning
  - Only affects the central parts of the star – outer layers retain their pre-SN composition

# Explosive Nucleosynthesis

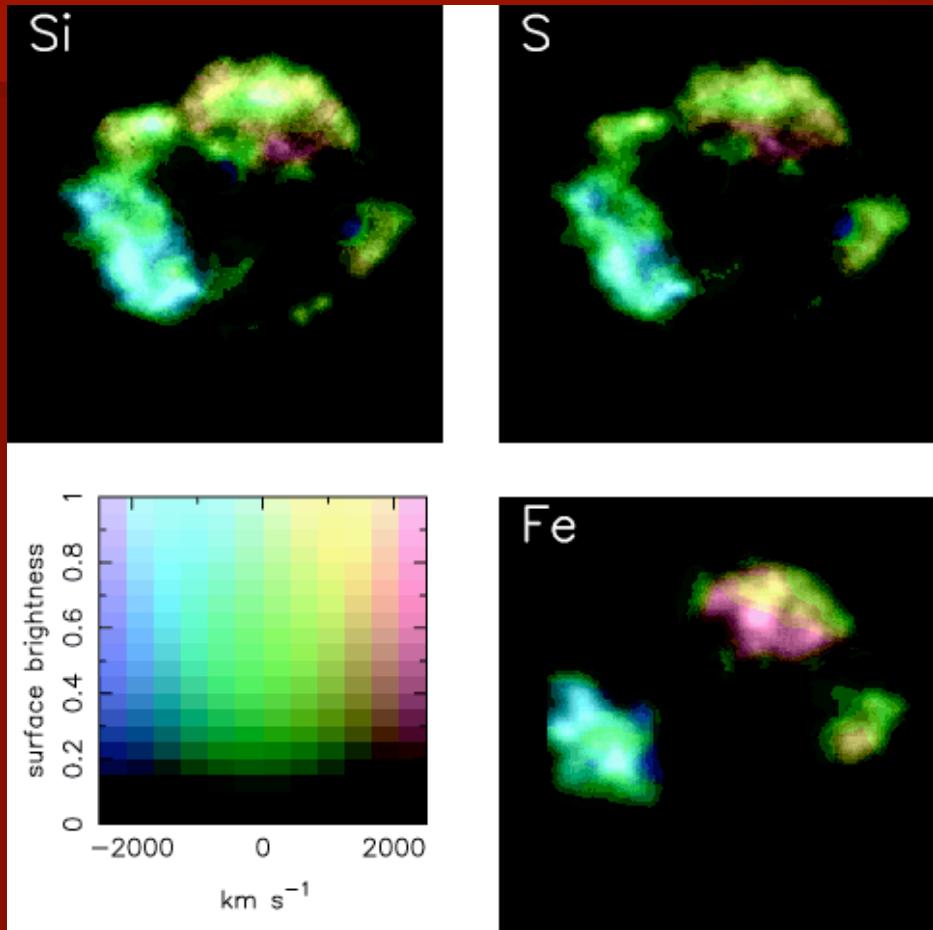
Process	T ( $10^9$ K)	Main Products
Explosive complete Si-burning	5.0	"Fe", He
Explosive incomplete Si-burning	4.0	Si, S, Fe, Ar, Ca
Explosive O-burning	3.3	O, Si, S, Ar, Ca
Explosive Ne/C-burning	1.2	O, Mg, Si, Ne

# OVERTURNING OUR VIEW OF Cas A



Hughes, Rakowski, Burrows, and Slane 2000,  
ApJL, 528, L109.

# Cas A - Doppler Imaging by XMM

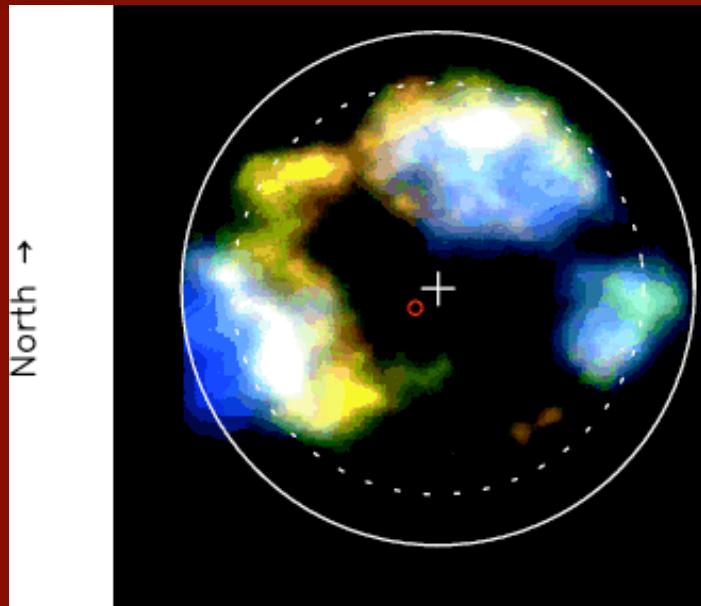


- ✓ Similar velocity structures in different lines
  - SE knots blueshifted
  - N knots redshifted
  - Tight correlation between Si and S velocities
- ✓ Fe
  - Note velocity distribution in N
  - Extends to more positive velocities than Si or S

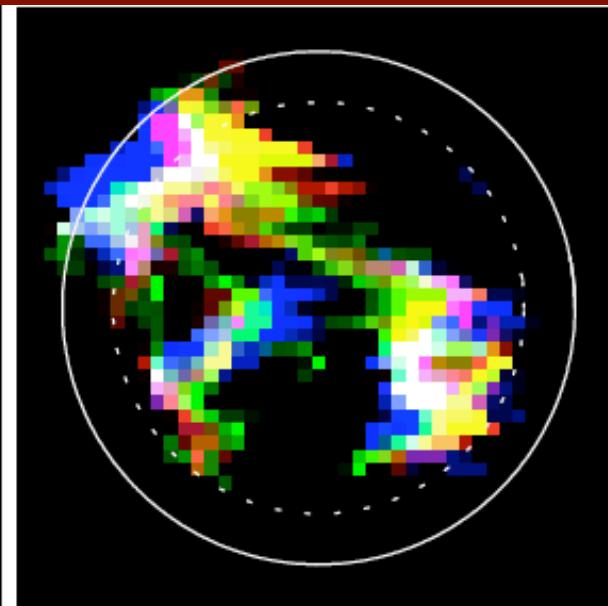
Willingale et al 2002, A&A, 381, 1039

# Cas A – 3D Ejecta Model

“Plane of the sky”



“Rotated”



Red: Si K $\alpha$

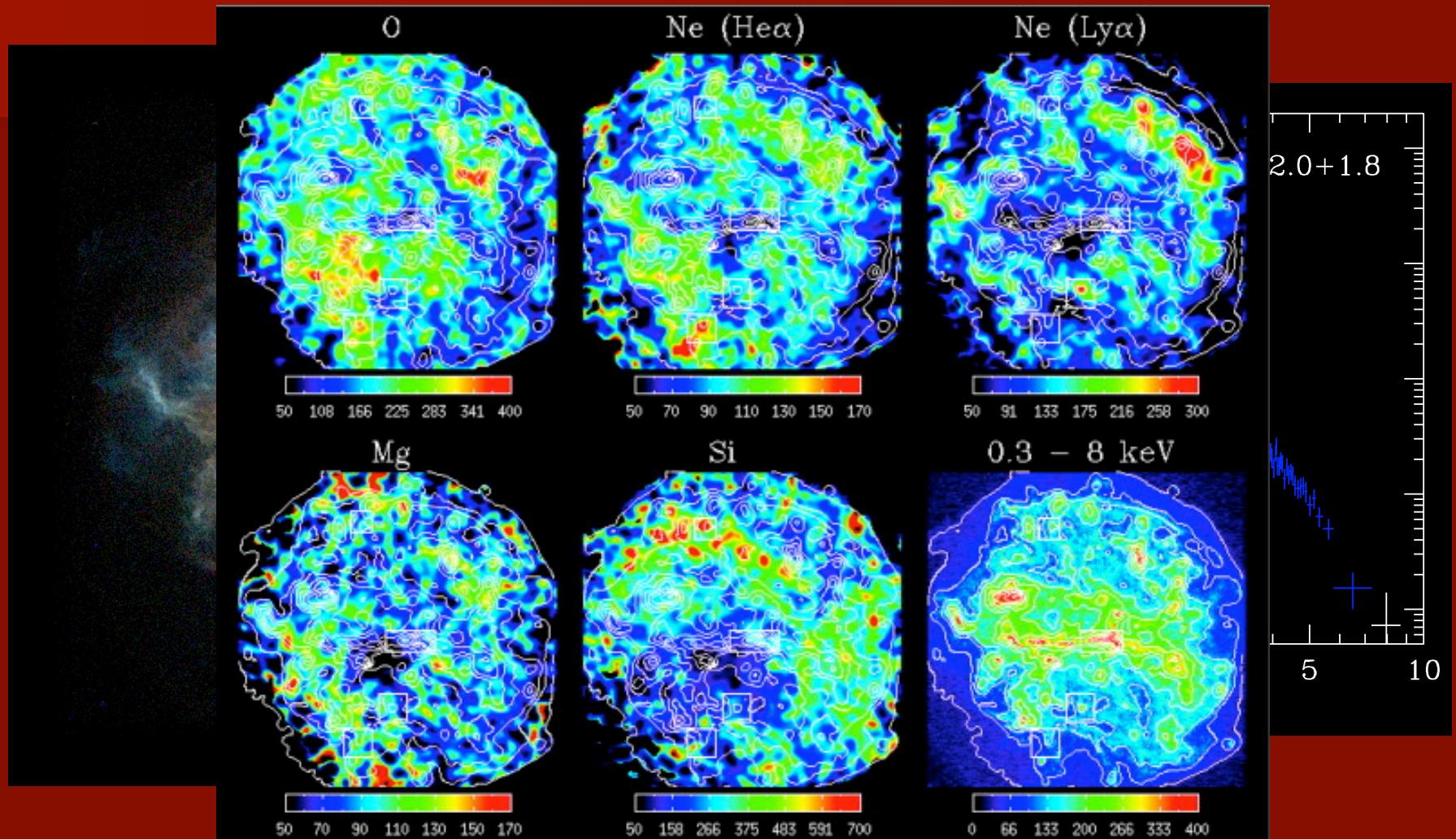
Green: S K $\alpha$

Blue: Fe K $\alpha$

Circle: Main shock

Fe-rich ejecta lies outside Si/S-rich ejecta

# Oxygen-Rich SNR G292.0+1.8



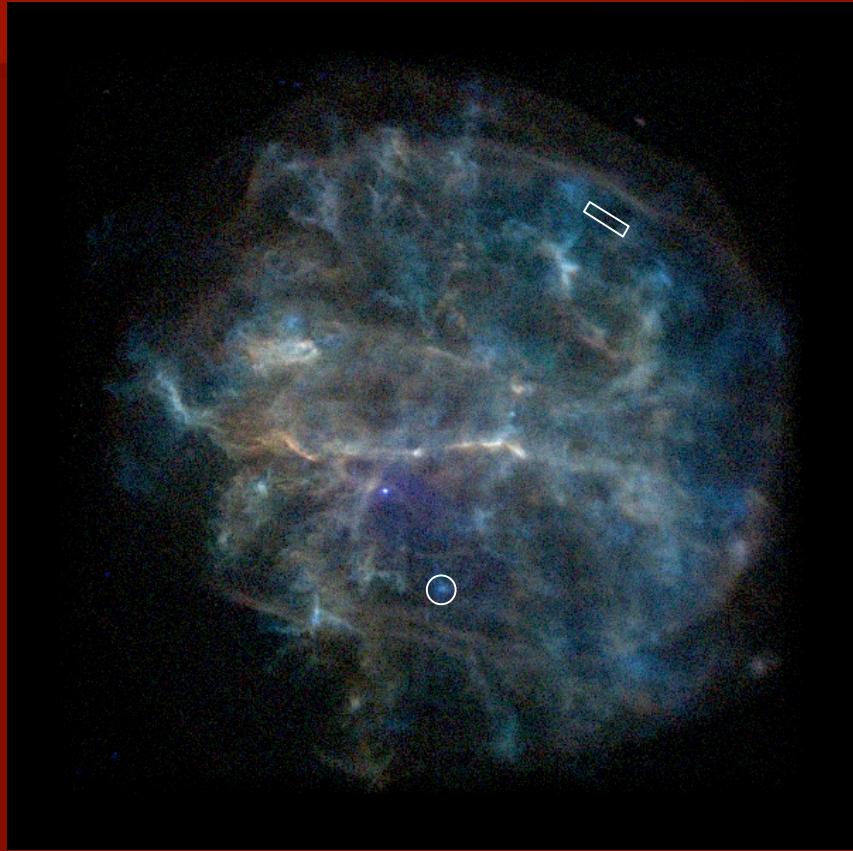
Park et al 2001, ApJL, 564, L39

May 6, 2003

Constellation-X Workshop

9

# Oxygen-Rich SNR G292.0+1.8

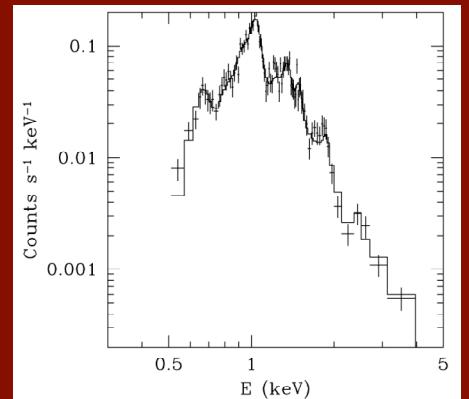
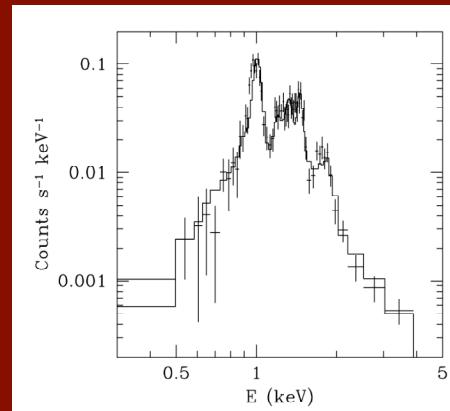


## Ejecta

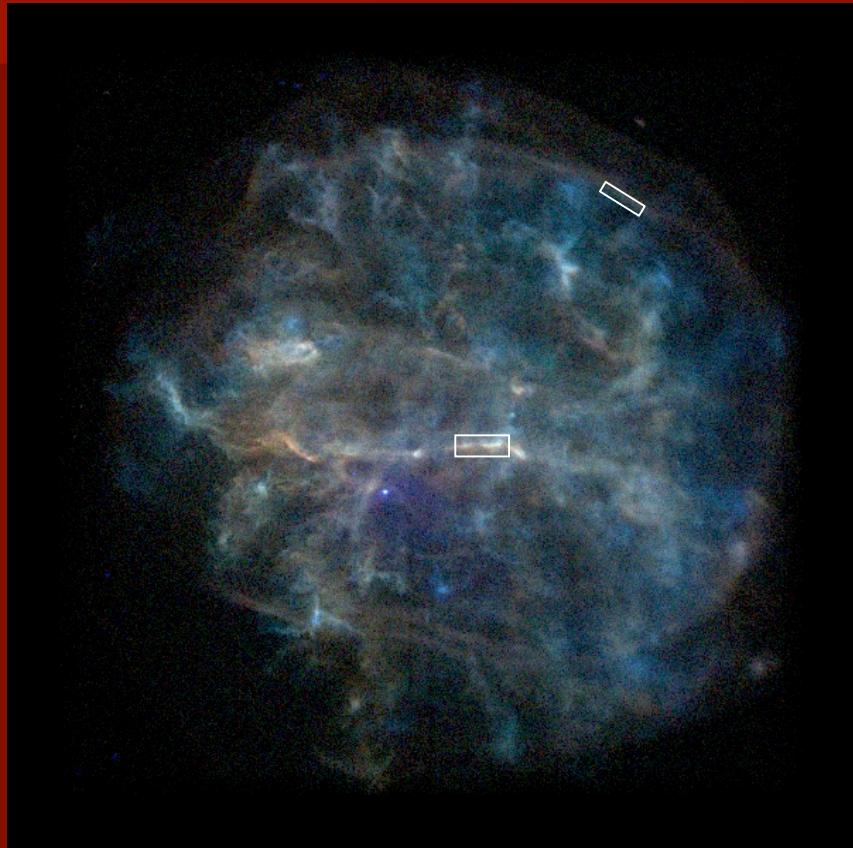
Rich in O, Ne, and Mg, some Si

$[\text{O}]/[\text{Ne}] < 1$

No Si-rich or Fe-rich ejecta



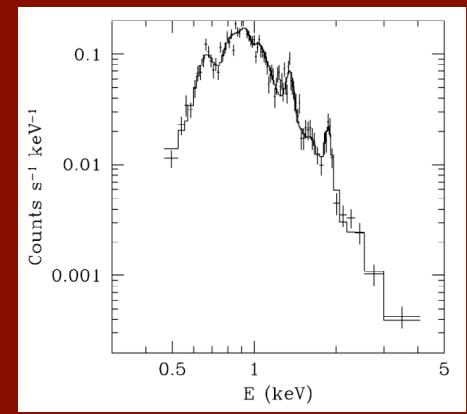
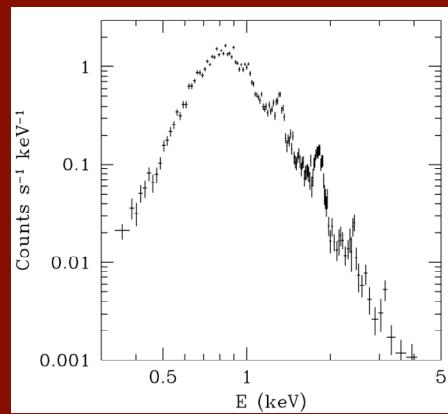
# Oxygen-Rich SNR G292.0+1.8



Normal Composition, CSM

Central bright bar – an axisymmetric stellar wind (Blondin et al 1996)

Thin, circumferential filaments enclose ejecta-dominated material – red/blue supergiant wind boundary

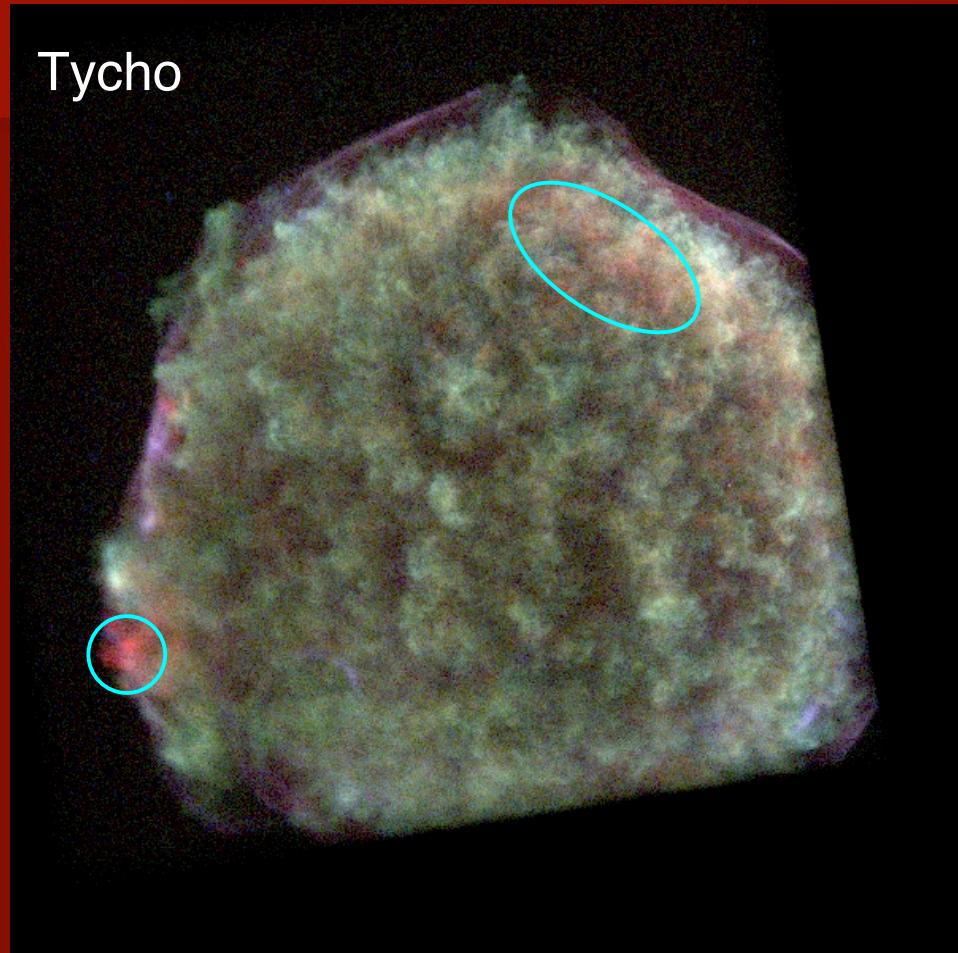


# Thermonuclear Supernovae

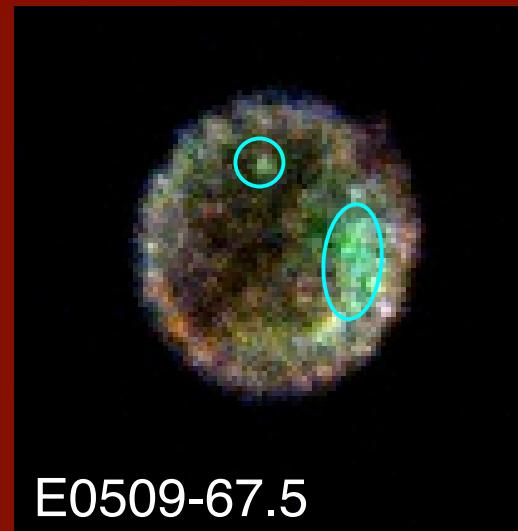
## ▼ SN Ia (Hoyle & Fowler 1960)

- No hydrogen, a solar mass of  $^{56}\text{Ni}$ , some intermediate mass elements (O, Mg, Si, S, ...)
- Subsonic burning (deflagration) of approx. one Chandrasekhar mass of degenerate C/O
- C-O white dwarf accreting H/He-rich gas from a companion
- No compact remnant
- Mean rate  $\sim 0.3$  SNU

# Identifying Remnants of SN Ia

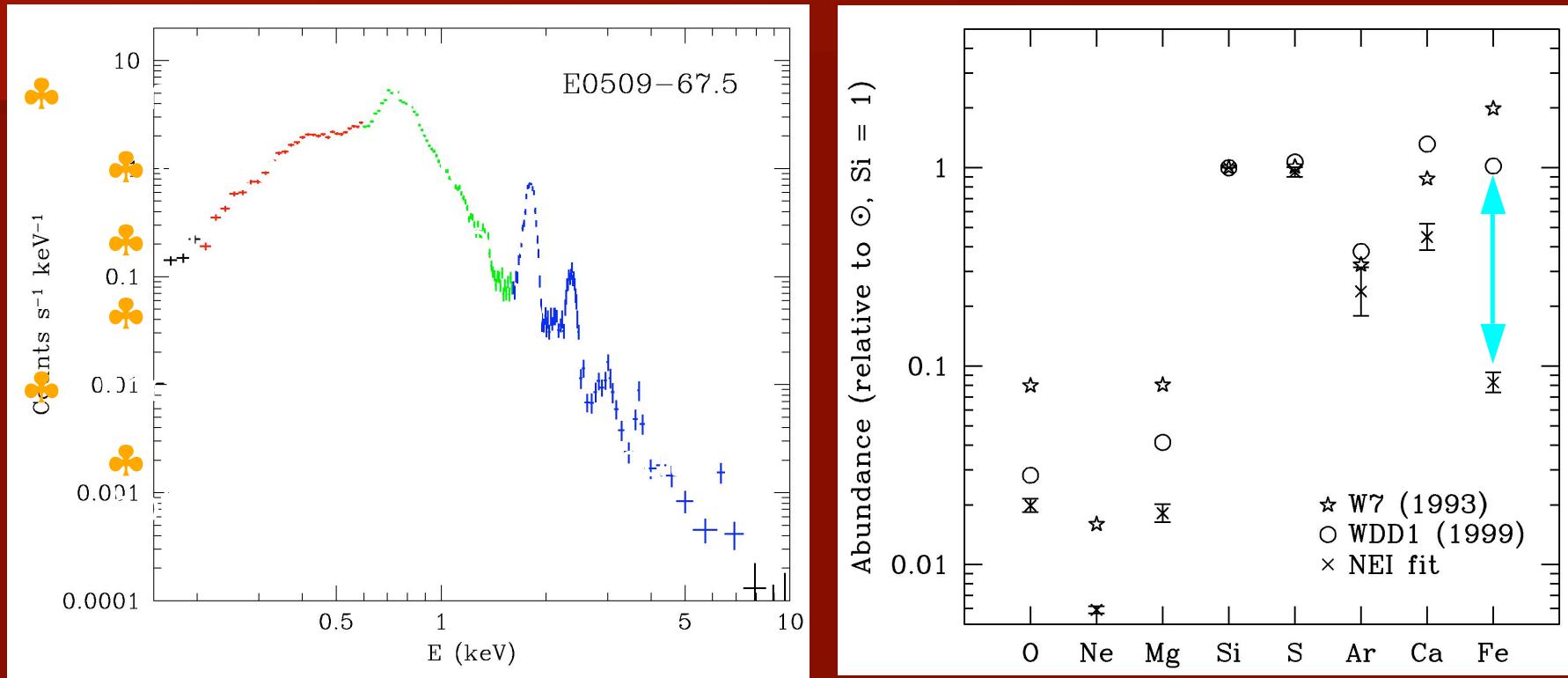


- ▼ Balmer-dominated SNRs (partially neutral ISM)
- ▼ Ejecta abundances (Si and Fe rich, poor in O and Ne)
- ▼ Remnant structure (uniform ISM, “smoother” ejecta, little spectral variation)



E0509-67.5

# SN Ia Spectra and Abundances



W7: Nomoto et al 1984, Thielemann et al 1993

WDD1: Iwamoto et al 1999

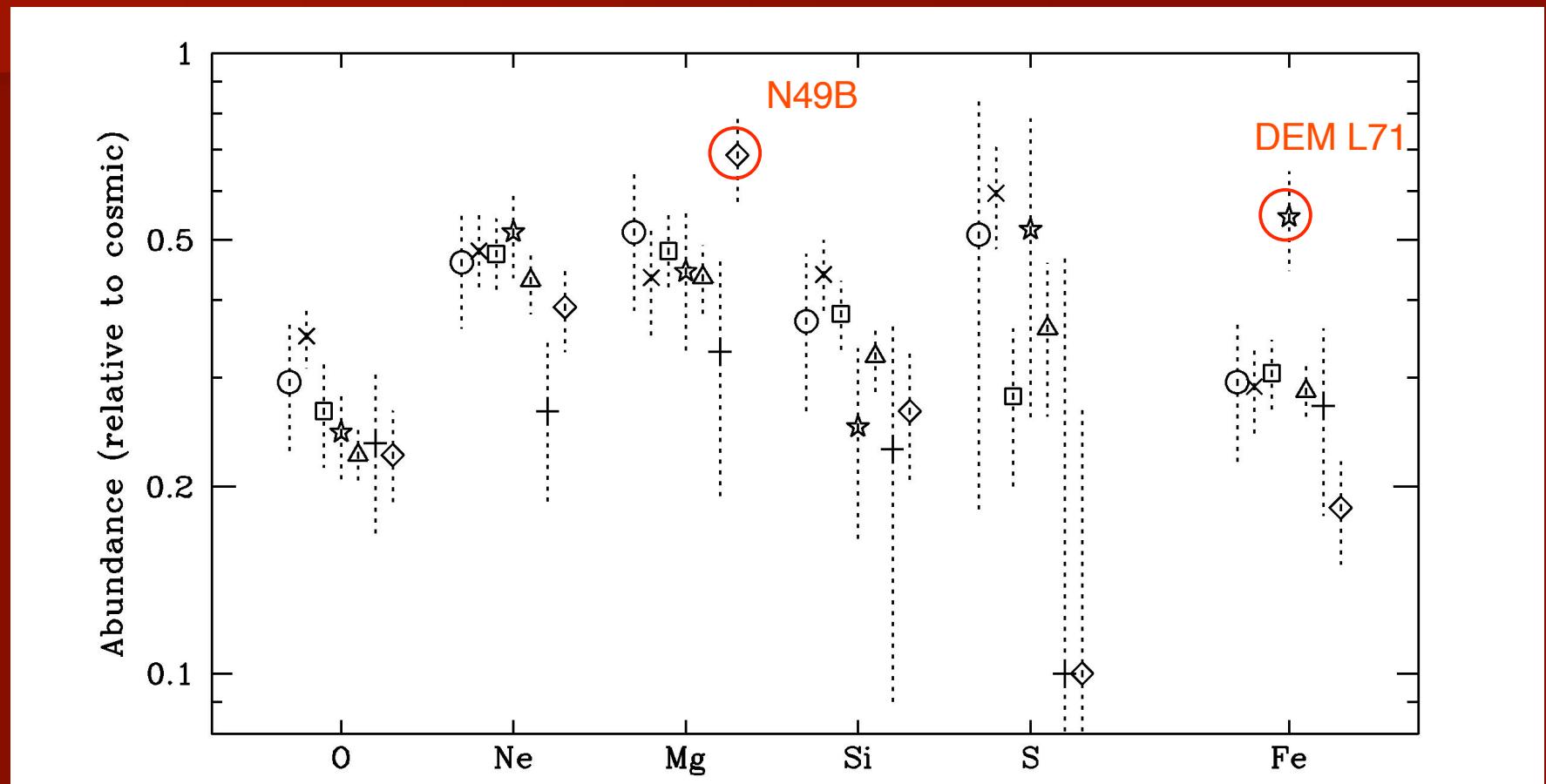
NEI fit: Warren et al 2003

# ISM Abundances of the LMC

- ▼ Using SNRs as a probe of the ISM
- ▼ 7 SNRs, ages from 2,000 yr to 20,000 yr
- ▼ Data from *ASCA*
- ▼ Spectra calculated for evolutionary models  
(Sedov solution)
  - spatial variation
  - temporal variation

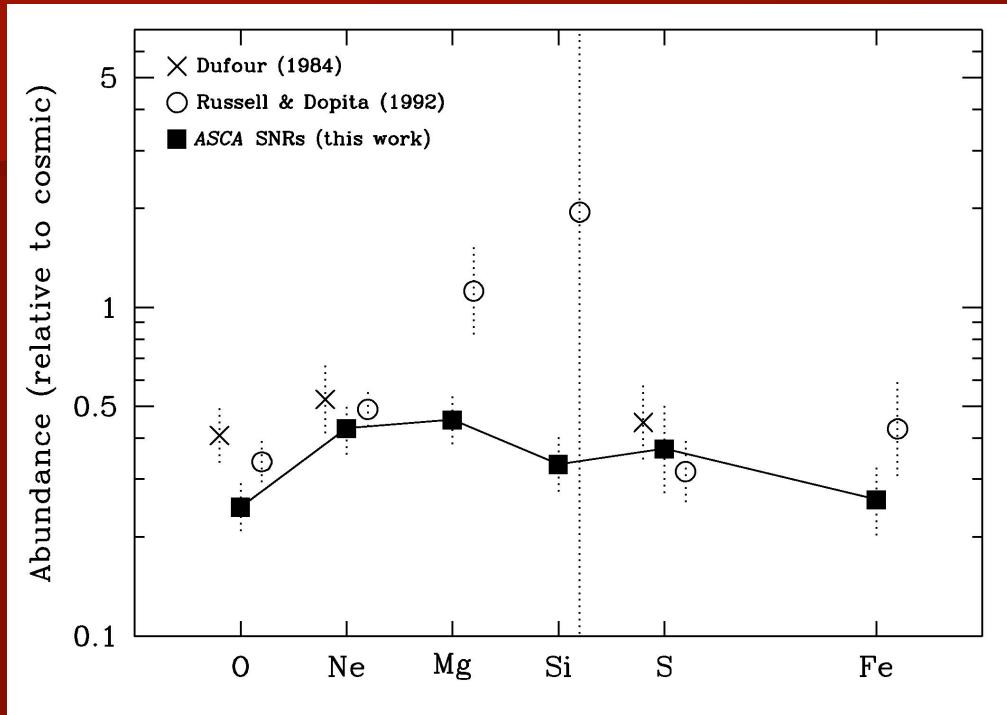
# LMC SNRs: Integrated Abundances

From fits to ASCA global X-ray spectra of 7 evolved LMC remnants



Hughes, Hayashi, & Koyama 1998, ApJ, 505, 732

# LMC Metal Abundances



Species	HHK98	Duf84	RD92
O	8.21(7)	8.43(8)	8.35(6)
Ne	7.55(8)	7.64(10)	7.61(5)
Mg	7.08(7)	...	7.47(13)
Si	7.04(8)	...	~7.8
S	6.77(13)	6.85(11)	6.70(9)
Fe	7.01(11)	...	7.23(14)

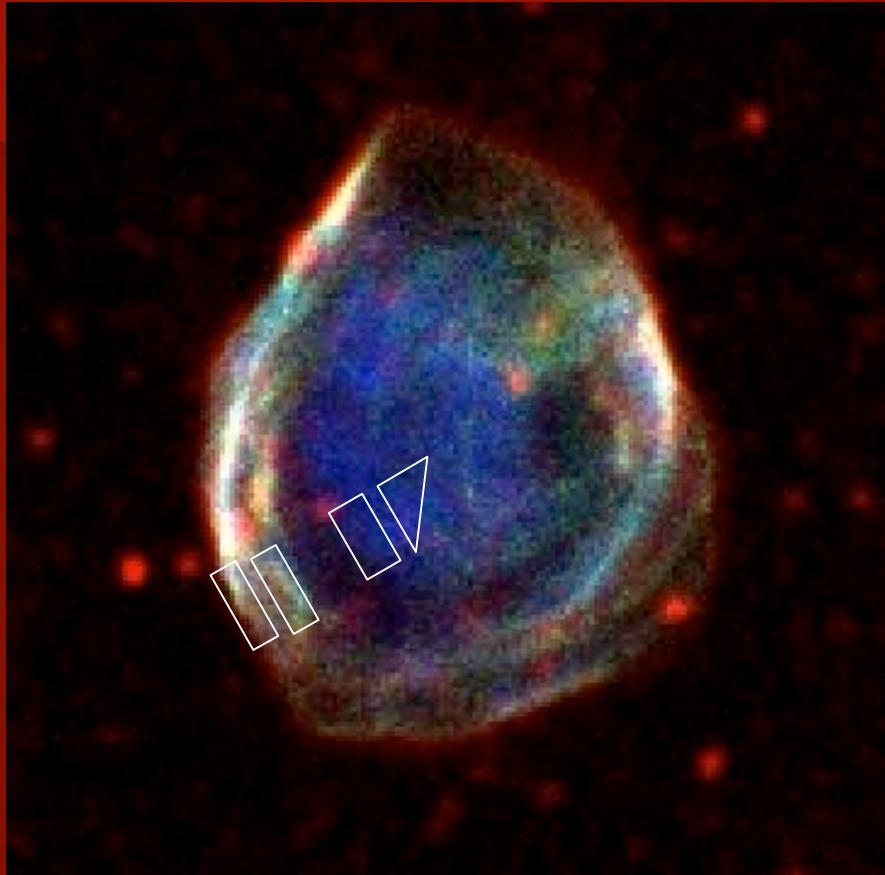
HHK95: ASCA X-ray SNRs

Duf84: UV/Optical spectra H II regions (Dufour 1984)

RD92: F supergiants (Mg, Si, Fe) (Russell & Bessel 1989)

H II regions, SNRs (O, Ne, S) (Russell & Dopita 1990)

# DEM L71: Fe-Rich Ejecta

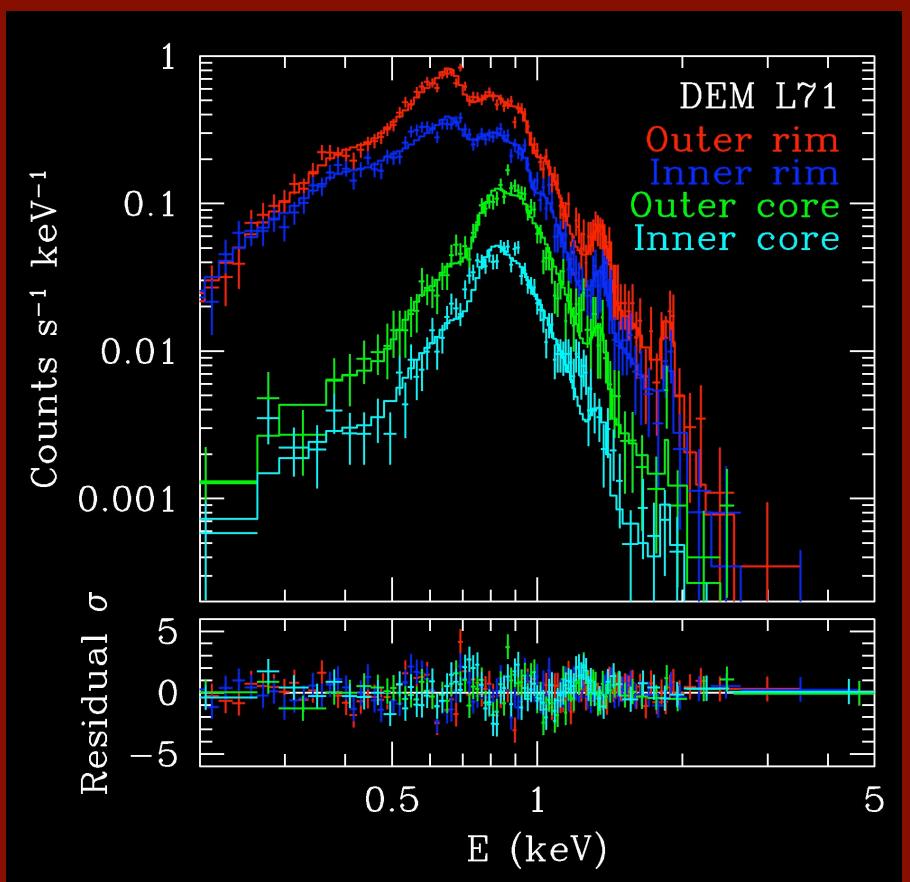


Hughes, Ghavamian, Rakowski, & Slane 2003, ApJ, 582, L95

Middle-aged LMC SNR

–36" (8.7 pc) in radius

–4,000 yrs old



# Properties of DEM L71 Ejecta

- Outer rims: lowered abundances, ~0.2 solar (LMC ISM)
- Core: enhanced Fe abundance,  $[Fe]/[O] > 5$  times solar (ejecta)
- Thick elliptical shell, 32" by 40" across (3.9 pc by 4.8 pc)
- Dynamical mass estimate

$$r' \sim 3.0$$

$$M_{ej} = 1.1 M_{ch} (n/0.5 \text{ cm}^{-3})$$

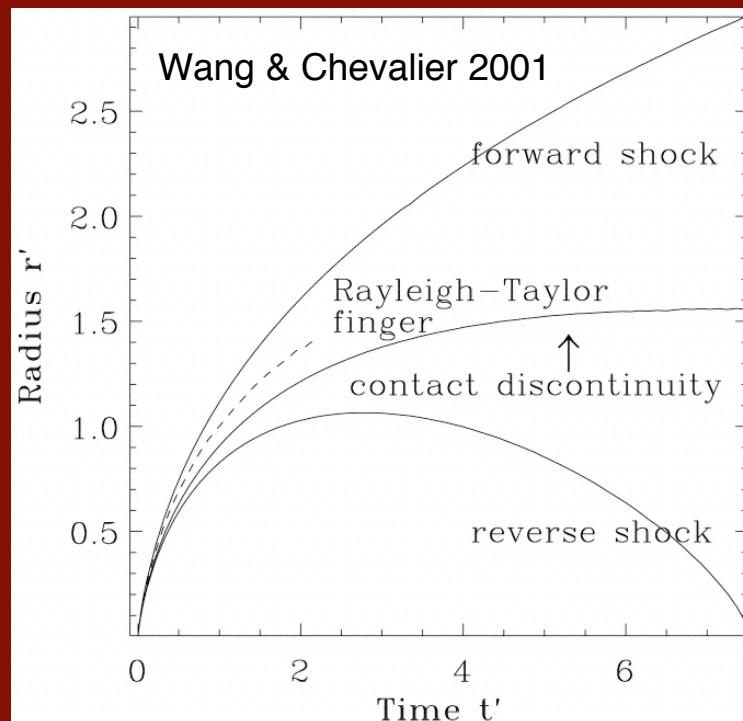
- EM mass estimate

$$EM \sim n_e n_{Fe} V$$

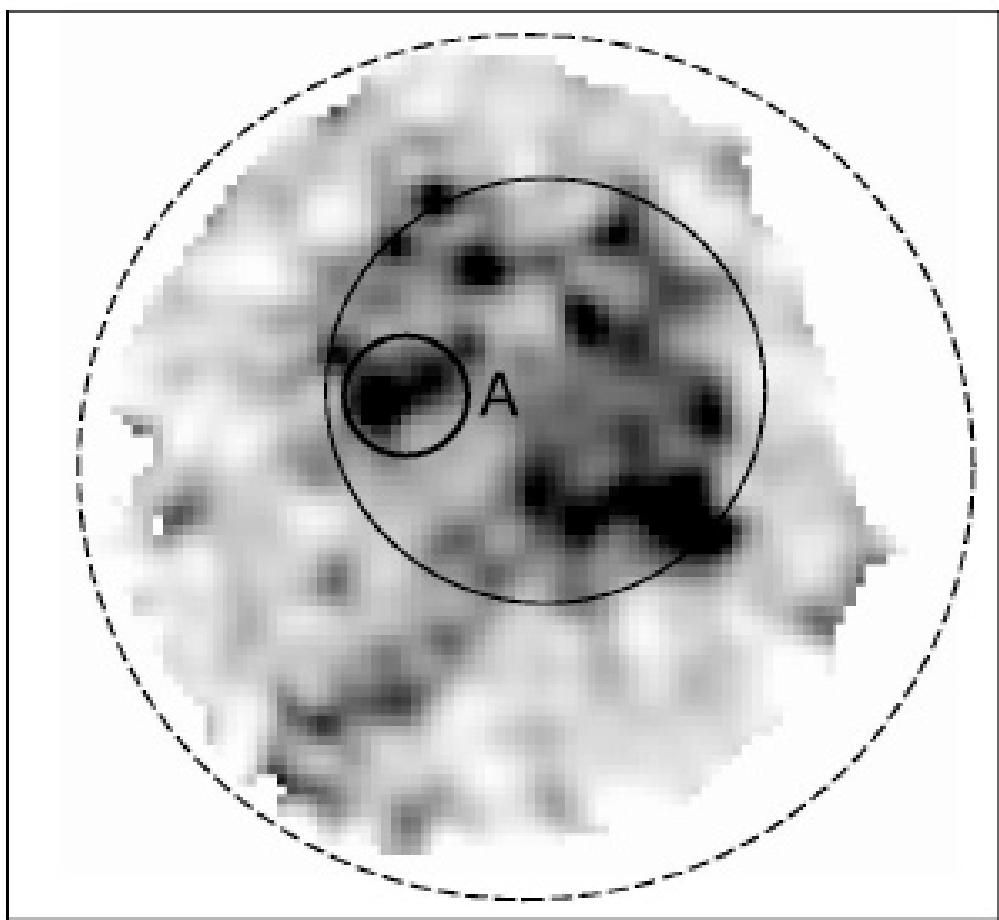
$$M_{Fe} < 2 M_{sun}$$

- Main error: source of electrons

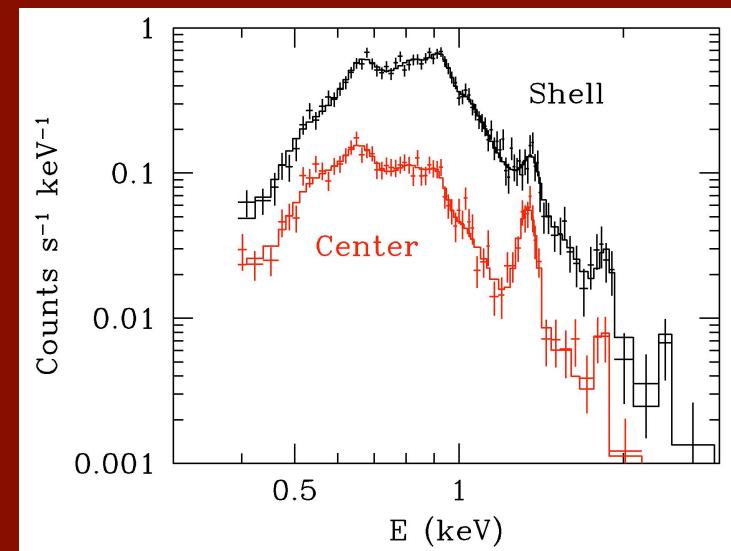
Fe-rich, low mass  $\rightarrow$  SN Ia



# N49B



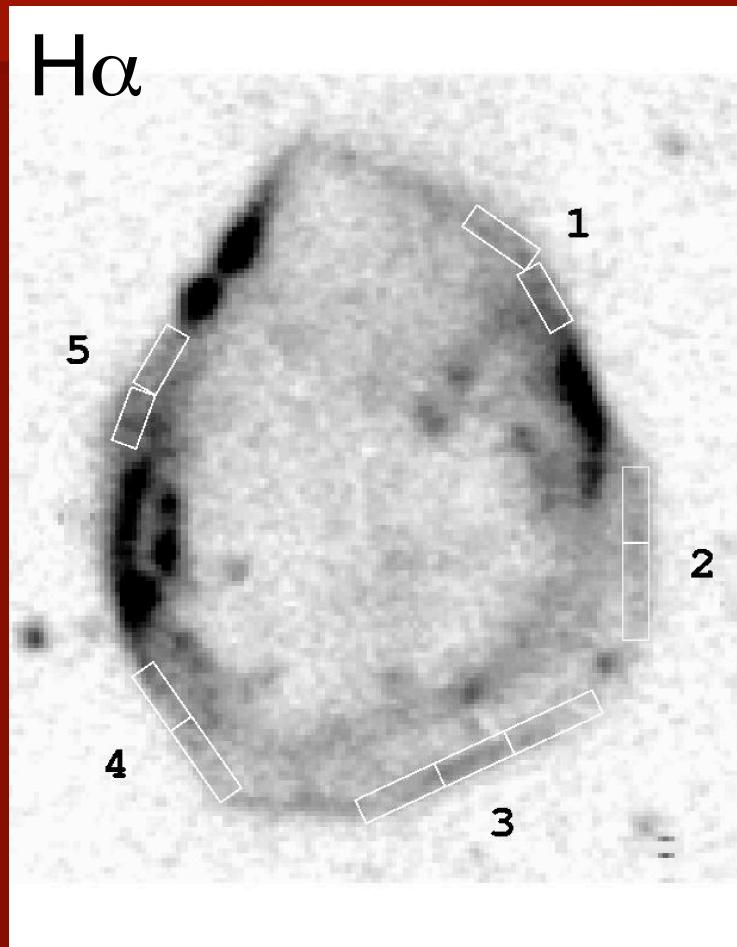
- ▼ Middle-aged SNR
  - 80" (19 pc) in radius
  - 5000-10,000 yrs old
- ▼ Bright and faint rims
  - LMC composition
  - ISM density varies by x10
- ▼ Ejecta
  - Revealed by equivalent-width maps
  - Mg & Si rich, no strong O or Ne



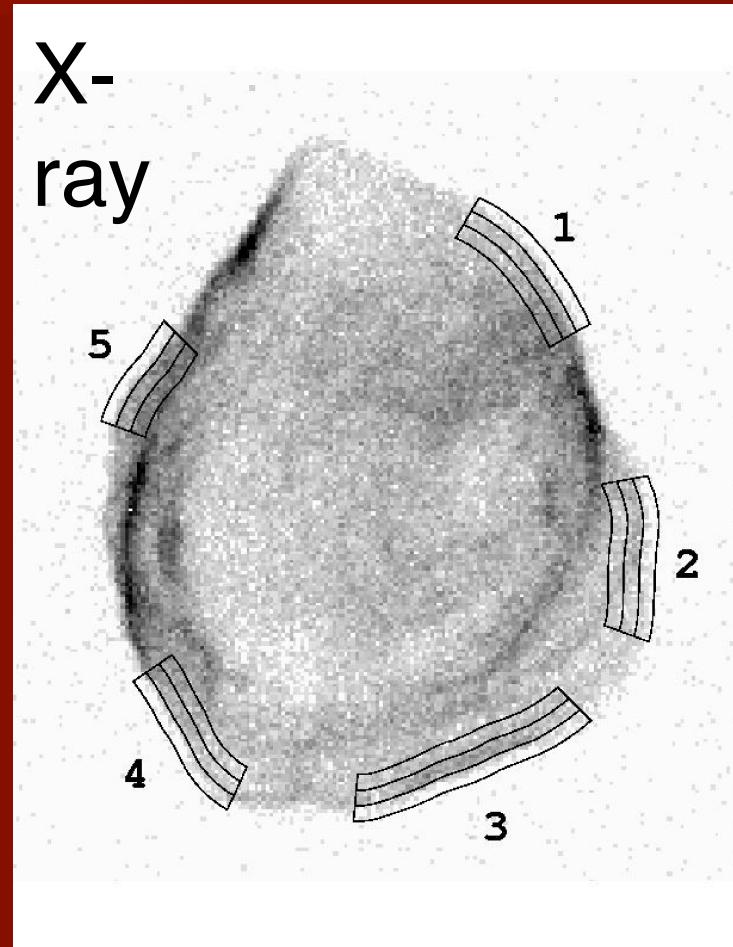
Park, Hughes, Slane, Burrows, Garmire, & Nousek 2003,  
ApJ, submitted.

# DEM L71: Shock Physics

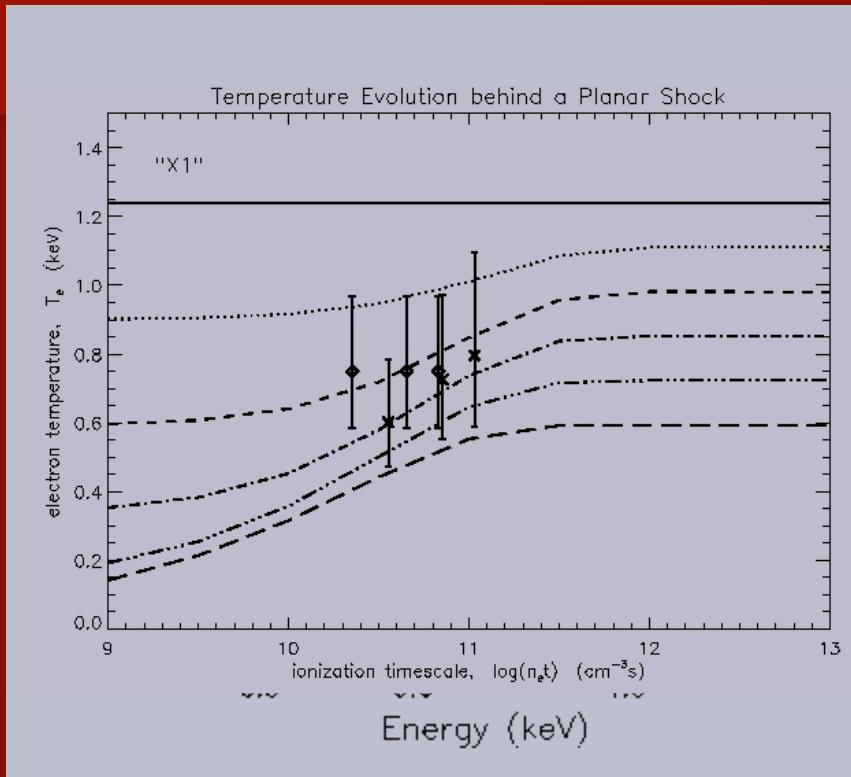
Nonradiative Balmer-dominated shock  
Measure post-shock proton temperature



X-ray emission from thermal bremsstrahlung  
Measure post-shock electron temperature



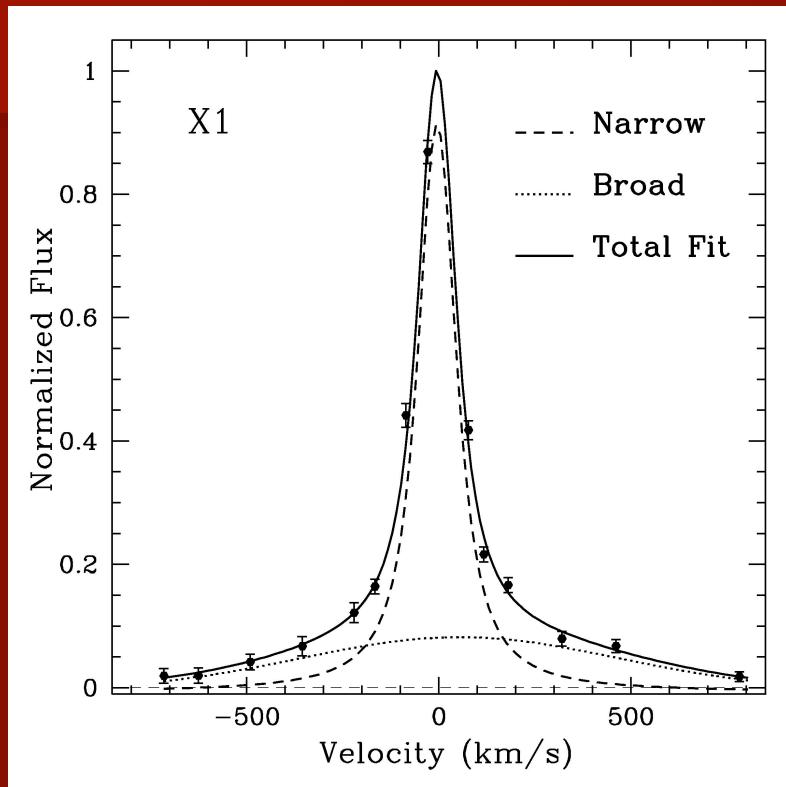
# Constraining the Electron Temperature



- ▼ Fit plasma shock models to 3 spatial zones to follow evolution of  $T_e$
- ▼ Study 5 azimuthal regions with sufficient Chandra statistics and broad H $\alpha$  component
- ▼ Available data cannot constrain  $T_e$  gradients
  
- ▼ Data do determine mean  $T_e$
- ▼ Suggest partial to complete temperature equilibration

Rakowski, Ghavamian, & Hughes 2003, ApJ, in press.

# Nonradiative Balmer Shocks



- ▼ Nonradiative means that a radiative (cooling) zone does not form
- ▼ Low density (partially neutral) gas
- ▼ High velocity shocks
- ▼ Narrow component: cold H I overrun by shock, collisionally excited
- ▼ Broad component: hot postshock protons that charge exchange with cold H I

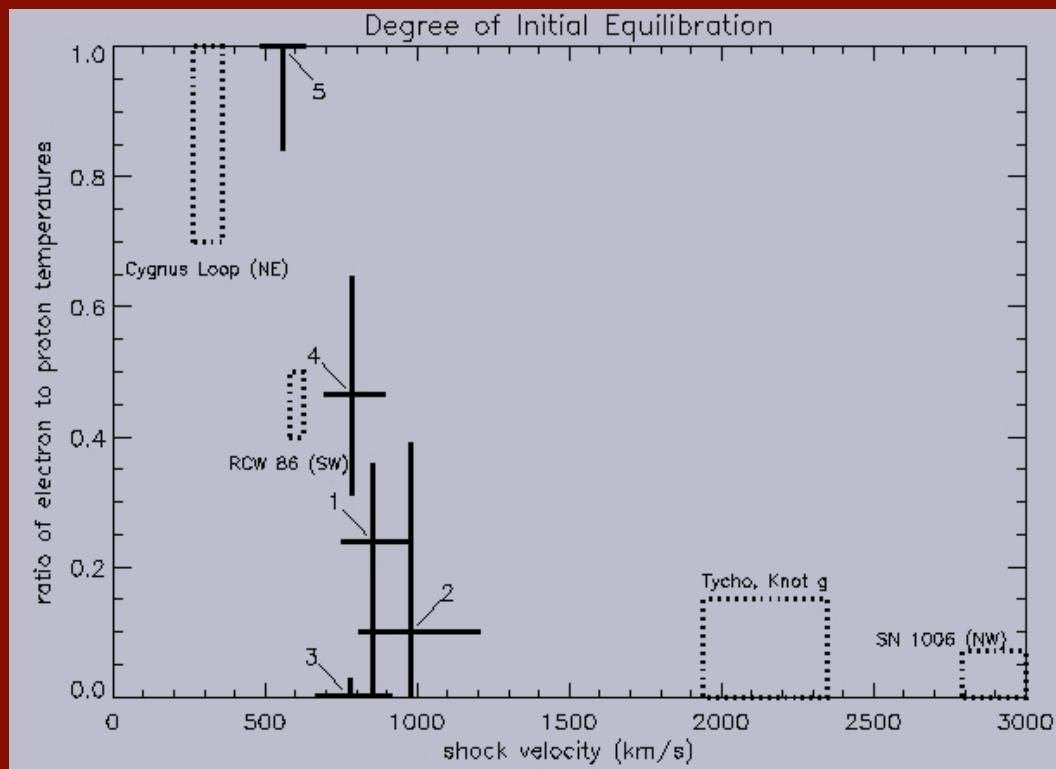
(Chevalier & Raymond 1978; Chevalier, Kirshner, & Raymond 1980)

Width of broad component yields post shock proton temperature

Ghavamian, Rakowski, Hughes, and Williams 2003, ApJ, in press.

# Results on $T_e/T_p$ from DEM L71

- Shows trend: higher equilibration for slower shocks
- X-ray/H $\alpha$  results consistent with other purely H $\alpha$  ones



# Constellation-X Capabilities: Requirements for SNR studies

- ✓ Spectral resolution
  - Velocity resolution <1000 km/s for O lines
- ✓ Spatial resolution
  - <5" (minimum for LMC SNRs)
- ✓ Significant low energy response
  - Neutron star cooling
- ✓ Timing
  - <10's msec for pulsar studies



The End